SANDIA REPORT
SAND2001-0940
Unlimited Release
Printed April 2001

Robotic Concepts for Small Rapidly Deployable Forces

Robert Palmquist, Jill Fahrenholtz, and Richard Wheeler

Prepared by
Sandia National Laboratories
Albuquerque, New Mexico 87185 and Livermore, California 94550

Sandia is a multiprogram laboratory operated by Sandia Corporation,
a Lockheed Martin Company, for the United States Department of
Energy under Contract DE-AC04-94AL85000.

Sandia National Laboratories

Issued by Sandia National Laboratories, operated for the United States Department of Energy by Sandia Corporation.

Printed in the United States of America. This report has been reproduced directly from the best available copy.

Available to DOE and DOE contractors from
U.S. Department of Energy
Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831

Telephone: (865)576-8401
Facsimile: (865)576-5728
E-Mail: reports@adonis.osti.gov
Online ordering: http://www.doe.gov/bridge

Available to the public from
U.S. Department of Commerce
National Technical Information Service
5285 Port Royal Rd
Springfield, VA 22161

Telephone: (800)553-6847
Facsimile: (703)605-6900
E-Mail: orders@ntis.fedworld.gov
Online order: http://www.ntis.gov/ordering.htm

SAND2001-0940
Unlimited Release
Printed April 2001

Robotic Concepts for Small Rapidly Deployable Forces

Robert Palmquist and Jill Fahrenholtz
Intelligent Systems & Robotics Center
Richard Wheeler
Systems Research Department

Sandia National Laboratories
P.O. Box 5800
Albuquerque, NM 87185-1004

Abstract

In this paper several robotic and related technologies are highlighted that will enhance small unit operations for 21st century military personnel. Aspects of these suggested technologies will have impact in urban environments, in more rural mission settings, or in both. Technologies to aid humans in mission planning, surveillance, reconnaissance, fabrication, logistics and execution are described, as well as additions such as intelligent mobile vehicles to supplement the smaller, more distributed forces envisioned for 21st century missions.

CONTENTS

FIGURES

Robotic Concepts for Small Rapidly Deployable Forces

Introduction

As part of the Defense Science Board (DSB) 1996 Study of Tactics and Technology for 21st century Military Superiority, this report provides an overview of several technology areas where robotics and related technologies can have an impact. This paper presents a view which is very optimistic about the future of robotic systems in military operations ranging from the forward edge of the battle area to the ships offloading supplies on the littoral. This view is in contrast to the recent pessimism in the U.S. about robotic systems both by the military and the larger civilian user and supplier community. The reasons for this optimism are enumerated in the paper.

The DSB study is focusing on several mission scenarios where small unit operations in the 21st century can replace larger forces needed for the same type of mission today. The mission scenarios for the study include urban environments, settings such as Desert Storm where a combined arms attack must be halted, securing territory, extended offensive operations, and extracting forces. We describe technologies that apply over a broad range of these scenarios; only a few will be described relative to specific missions. Our discussion focuses on local unit operations, which are operations within a range of 30-50km, and small unit operations in urban environments performing surveillance and reconnaissance.

Since the DSB study is focused on operations in approximately 2016, the technologies that we considered are those that will be ready for use in the field at that time; this means that they can be in R&D today, or could realistically be started in R&D in the next 5 years. This gives the technologies from the late 1990's to the late 200X time frame to become mature and fieldable. The last five years are reserved for taking the technologies into the field, implementing training environments, and incorporating them into the policies and procedures of the armed forces; this is a more cultural and administrative phase of technology development and implementation.

This paper conceptualizes "robot" in several different ways. At the most narrow, a robot is a mechanical device - either a mobile vehicle, or a manipulator, or a combination of both. At the most expansive, a robot is an integrated system which contains a multiplicity of components which could be related to carrying out a mission, such as a mine-sniffing device, or to making the robot itself intelligent. An example of the latter component would be sensors and algorithms which allow a mobile robot to autonomously navigate around obstacles in its path. [1]

The technology areas which are described in this report will be grouped into the following areas: Mobile Intelligent Vehicles; Human-Assisted Platforms, both teleoperation in the battlefield, and logistical and other aids for tracking, loading, and unloading of cargo and equipment; Field Maintenance and Repair Aids; Extremely Rapid Programming and Deployment Environments; and Advanced Training and Simulation. Each section defines the technology area, assesses its current state of technology, identifies the emerging capabilities in that area, and predicts the impact of this technology area on small unit operations.

The Enablers

Advances in a host of key areas have been made in recent years - far too many to discuss in this paper. However, here are some which are at the top of the enabler pile:

- The architecture and the technology have been developed which permit the rapid, reliable integration of complex intelligent systems. Integration had been one of the most difficult aspects of all intelligent robots whether industrial or military.
- The intelligent machines technology community has made strides in the construction of architectures and technologies for systems which contain a mixture of autonomy and human-in-the-loop. These advances, coupled with those in communication technology, will provide radically new opportunities to remove troops from harm's way, and to gather information about the battlefield.
- Technology has been developed which permits rapid, reliable mission reconfiguration of a system *in the field*. In this paper, we go so far as to postulate that all-new, smart robots, including both hardware and software components, will be constructed in the field depending on the needs of the operation.
- Developments in the micro-world will permit the use of intelligent machines in new ways. Macro-, mini- and microrobots will be in use -- perhaps even in collaboration. In an urban sniper situation, for example, a mobile robotic "mother ship" camouflaged as a brick will enter a building, climb the stairs and offload smaller robots, disguised as waste, which will roam the hallways searching out snipers. These robots will "chain communicate" with each other and, via the mother ship, with the operation commander.

Intelligent Mobile Vehicles

Definition

This section discusses mobile intelligent sensing platforms for applications such as surveillance and inspection; searching, following and tagging; and/or locating and identifying targets. These platforms can be land-based but are not limited to that domain. They can be large, such as unmanned fighter aircraft, or small, such as an "invisible" surveillance device. However, in each instance these systems will have on-board intelligence, have some form of autonomous capability, and be able to cooperate with other systems in achieving a desired outcome.

Current State of Technology

The "intelligence" of mobile vehicles still limits such systems to operate only in the domain of known environments. For example, navigation down a known hallway is certainly available.[2] Recently there have been demonstrations of vehicles driving themselves on roads at highway speeds.[3] Mobility and transport have been demonstrated by projects such as Dante's crater exploration in Antarctica.[4] All of these systems are large in size. Miniaturization of these systems is still an area of evolving capabilities. Such miniaturized systems have been developed but they are mostly only operated in laboratory environments, are tethered or have a very limited operating duration (e.g., 30 minutes), have limited mobility (e.g., typically "wheeled" systems) and have very limited onboard intelligence.[5-7]

Emerging Capabilities

Miniaturization -- Moving to the Small and the Inexpensive: Miniaturization in the electronic world has revolutionized our daily lives. Are the emerging miniaturization capabilities in the mechanical world, such as micromachining and LIGA parts, going to generate the same effect?[8] In the next decade, motors of $80mm^3$, fuel cells with densities of 50 joules/mm^3 and actuators of 8 mm^3 will all be available. These are technologies which are going to revolutionize the battlefield as is described in the Impact Section below.

Systems That Learn on the Job: Intelligence for mobile systems will no longer be limited to our ability to capture human-knowledge in algorithms and expert systems. Natural learning approaches, genetic algorithms, and Linked Learning Classifier systems will be coupled with systems, both individual platforms and "swarms" of platforms, to form an adaptable, reliable and optimal system deployment capability.[9]

Distributed Intelligence and Sensor Systems: Most of the recent benefits of information technology are going, not into more powerful computers, but into more widely distributed, networked intelligence. This truism of commercial life can be applied to the battlefield with even greater force. Several factors suggest that such distribution is not only possible but optimal. It may be a more cost-effective solution to deploy less sophisticated products manufactured in the millions rather than a handful of very sophisticated products costing tens of millions. In the military realm, thousands of sensors could be networked and their information fused together to form a more complete description of the changing military situations.[10] Dispersion is also beneficial for locating an object. A hundred low-power noses can detect, and more important, track a scent better than a single high-power nose stuck in one place.[11] Distributed systems are also more robust against accidental failure than large ones. The greater the desired reliability, the greater the advantage of distributing capacity into smaller units.

Major Technical Challenges: The major technical challenges for miniature systems are production of low cost platforms, energy consumption, communications, on-board sensor systems including data interpretation, transport mechanisms (e.g., moving from "wheels" to devices that can swim, hop and/or fly), guidance and navigation systems and behavior modes including cooperating behaviors.

Impact

Urban Operations -- Find the Sniper: Urban operations provide unique challenges in the areas of surveillance, intelligence gathering, and targeting: how many people are in the building, what's the layout of the structure, are there civilians and/or hostages present, if so, where are they located, and how can I neutralize the target without causing damage to surrounding areas? All of these questions can be answered in the future with the use of intelligent mobile vehicles. In the scenario of a sniper being located in an urban area the first element is to deploy a larger type vehicle capable of surviving small-caliber gunfire. The primary purpose of this vehicle is transport and deploy smaller devices which will ultimately perform the desired mission. This larger vehicle could be deployed behind safe lines (such as is depicted in Figure 1) or it could be a vehicle which is intentionally left throughout the urban area but "hidden" from view such as the "brick" shown in Figure 2. This vehicle, which would be capable of self navigation, would attempt to enter the sniper's building. This could mean breaking through a barrier or more likely deploying the smaller mobile devices which would be capable of penetrating barriers through means other than force. Such an example is depicted in Figure 3 where these smaller devices, disguised as bottle-caps, would be capable of jumping up steps and sliding under doors, or in Figure 4 where the devices float along the outside of the structure. These smaller devices would cooperate with each other as they disperse throughout the building, acquire the desired knowledge, and perhaps even assist in the neutralizing of the sniper by being a homing device for a precision weapons system or being the weapon system itself. Having acquired the desired information they could transmit this data directly back to the home base or return to the transport vehicle which then in turn would deliver the information back to the original deployment location.

<u>In the Field -- The Small and the Many:</u> Large numbers of miniature intelligent machines will alter battlefield and peacekeeping operations in several areas. These systems will employ stealth, remote operations, remote transmission and multi-agent cooperation to enhance the operations of a small, rapidly deployable troop force. Systems composed of millions of miniature intelligent machines, carrying sensors, emitters, and mini projectiles, will, in concert, be able to detect, track, target, and land a weapon on any military object. These systems may work in small groups to identify a facility's activities, generate a map of the structure and provide targeting (Figures 4 and 5); may be dispersed across the entire battlefield region to locate and track vehicles (Figure 6); or may be used in an urban setting to identify and neutralize targets with minimum collateral damage (Figure 2).

<u>The Secret and the Patient</u>: Pop-up warfare describes the battlefield or urban environment in which the means of war/peacekeeping are quiet and hidden until they rise and engage. [12] Mobile miniature intelligent systems which can hide until needed, be inert until activated, and be forever disabled when the mission is completed, will impact not only the deployment of operations but also the withdrawal after the mission is completed.

<u>The Powerful and Agile:</u> Small numbers of larger intelligent machines will enable new capabilities in weapons and troop deployment. Precise and high performing remotely operated aerial platforms will redefine stealth, surveillance and targeting operations. This will be realized by the enabling capabilities described in the next section.

Human-Assisted Platforms: Battlefield and Peacekeeping Operations

Definition

Human-assisted platforms are systems which are designed such that the operator(s) and the computing system(s) share control of the device(s). In this approach there are two modes of operation. In the first mode the operator defines high level tasks (e.g., fly to this location) while the computing system performs the lower level operations required to complete the task (e.g., generate the appropriate path to take, and couple the flight controls to this trajectory to reach the desired location). In the second mode, the operator has complete control of the platform with the computing system running in the background to verify the correctness of the operator's inputs.

Current State of Technology

<u>Teleoperation versus Telerobotic:</u> In a purely teleoperated environment the operator is required to control all aspects of the device at all times. Because of the limitations inherent in dealing with remote systems (e.g., lack of sensory input to the operator) this results in significant operator fatigue and reduced performance.[13] Using a hybrid *telerobotic* approach, where the operator can enter tasks and then allow the system to perform the lower-level operations (e.g., operator states "go to the other side of the building" and the system then determines an appropriate path to take using sensors and geometric information to achieve the task), reduces the demands on the operator and results in overall improved system performance.

Emerging Capabilities

<u>Stability Guaranteed</u>: One of the challenges of sharing control between human and computer inputs is to ensure the stability of the resulting control system. Since each operator is unique, the resulting transfer functions between the computing systems and the operator are going to be non-deterministic. This unknown time delay can cause instabilities in the system. The answer to this problem is twofold. First, decouple the operator's inputs from the computer's low level inputs to ensure that timing is no longer an issue. For example, have the operator input tasks for the system to perform (e.g., "go to next location") and then have the system "autonomously" perform this operation. This will be the optimum solution in many instances. However, for remote systems it does not allow the use of real-time "human-in-the-loop" control capabilities such as force reflection. To enable the latter, the use of passive control with modeling information versus classical feedback control becomes the solution. This is currently available in the control of robotic systems and could be extended to the control of other forms of mechatronic platforms. [14,15]

<u>Computer Co-pilot:</u> At times the operator may want to take over direct command of the platform and return to a teleoperated mode of operation. In this environment the computer systems would continually be checking to ensure the operator's inputs are valid. For example, if the operator is telling the vehicle to move forward but an obstacle is present, the computing system would override the operator's commands thus preventing damage to the vehicle. Improvements in sensors, modeling, database architectures, and information retrieval are making such real-time validation a near term capability.[15]

Lose the Keyboard: New capabilities in operator interfaces are rapidly emerging. Heads-up displays, stereo sound, audio inputs, natural language interpretation, 6-D+ input devices and textured force reflection are all examples of emerging technologies which will enable new capabilities in human-assisted platforms.[16]

Impact

No Seatbelts to Fasten: This technology will enable semi-autonomous remote operation of high performance platforms which will result in smaller troop force size, dispersed assets, with overall improved performance. Unmanned fighter aircraft, reduced personnel onboard ships, unattended surveillance platforms, materials that transport themselves, and peacekeeping platforms that are operated remotely are all examples of the types of systems which can be developed using this "Human-Assisted" approach. The degree of autonomy of these systems will increase as the technology evolves. Currently the operator is involved in controlling most of the platform's motions; in the future the operator will be able to input increasing higher levels of commands -- "investigate region", "determine enemy troops movements."

As further examples, battlefield and peacekeeping operations suggest many uses of human-assisted platforms. For example, securing territory is a typical mission objective in such operations. This mission, like any other, requires the basic elements of intelligent behavior: sensing (e.g., information gathering), planning (e.g., deciding what to do), and responding (e.g., implementing the plan through action). Human-assisted platforms will be valuable in providing the sensing and responding capabilities needed for securing territory, plus an intelligent mission planning assistant could be used to plan a securing strategy (most likely this would be a computer system, not a robotic platform). Such a plan would be based on prior knowledge of the territory, the local unit's resources, "securing territory" criteria, and real time information provided by the sensor and communication systems.

Sensing operations, used to improve situation awareness, could be conducted by human-assisted platforms such as UAVs or mobile ground sensors. A UAV could be deployed to scout portions of the target territory "over the next hill" or "beyond a designated wooded area." Flight paths could be preset by the human, generated autonomously by the UAV according to high level search objectives, or modified on-the-fly if the operator, because of incoming data, wanted to further investigate an area of interest. Search areas could be defined by the human, or flagged by intelligence on-board the UAV, or resident in a smart ground station. Information about threats (e.g., personnel, equipment, other potential targets) and local weather, road and terrain conditions would be used to determine strategic locations to control and preferred routes and resources needed to secure them. Paths for moving resources could be further refined by ground-based robotic "scouts" with suitable sensors that are sent out on patrol to detect and communicate the presence of mines. Prospective paths could be defined by an operator and the scout would confirm that the paths are free of mines (or other hazards).

Other human-assisted platforms could be employed for "responding" operations. Once paths toward strategic locations are identified, autonomous all-terrain "mules" could provide the brawn to carry gear, relieving soldiers' individual loads. When required, the motion of the mules could be assisted by a human operator; for example in crossing a stream. Once in control of the desired locations, the local unit could deploy robotic "sentries" (with fins, wheels, wings, tracks, or legs, depending on the local terrain) to monitor the surrounding area for new threats. The sentries might even be armed to defend against identifiable enemy intruders. Multiple sentries could coordinate themselves with higher level commands being given by an operator.

Human-Assisted Platforms: Logistical, Loading Docks, Littoral

Definition
Again, human-assisted platforms help the operator complete tasks that s/he assigns at a high level, while the computing system performs the lower level operations required to complete the task. Here human-assisted platforms are implemented in the planning of loading of ships or planes, performing this loading, the subsequent unloading, and helping to track cargo and equipment both on port side and on the theater side.

Current State of Technology
In deploying forces rapidly, getting equipment, supplies and troops to the theater are all important. Using past approaches, mistakes unfortunately have been made in getting the right supplies to the troops in a battle area, and deployment has been slowed because of the time it takes to load the supplies on the port side and unload them in the battle area -- especially when rough seas or other inclement weather prevents the final steps to delivery.

Impact
Rain or Shine -- We Deliver: The goal of force projection is to deliver troops and supplies to the battlefield anywhere in the world at any time. At present, the Navy will not or cannot deliver troops and supplies to areas that are at Sea State 3 or higher.[17] The use of stability augmentation systems (SAS) that are common among high-performance aircraft has the potential to overcome the problems associated with high sea states. SAS systems are used to eliminate the unstable behavior of cranes on cargo ships (e.g., excessive pitching and rolling caused by the waves) in the high sea states by employing feedback control. The feedback control compensates for the motion of the ship and produces an environment for the crane operator that is similar to low sea state operations. To further increase the speed of logistics operations, swing-free technology can be added to the crane once the SAS is in operation.[18]

Faster and Better: Swing-free cranes could be used both on port side and near the battle area to speed the loading and unloading of supplies. Swing-free crane technology reduces the time of movement of the crane by eliminating the swing at the end of the movement. (See Figure 7). [30] Without the need to keep swinging minimized, faster moves can be done and thus faster loading with fewer people. Swing-free cranes are available for port-side operations today. However, extensions to compensate for rough sea environments on the battlefield end of the trip have not yet been developed. This is an area which could be addressed in the very near term.[19]

What, Where, When and How: Logistical planning aids have been identified as a military need.[20] One aspect of this is maximizing the amount of cargo that can be transported in one trip through better planning of loading of ships and planes. This would speed delivery of equipment and supplies to the field. It is expected that operations like UPS and Federal Express will continue to develop the state of the art in this area. With smaller crew size and more dispersed operations, AGVs (automated guided vehicles) or automated stacker/retriever systems (AS/RS) could replace people for greater automation of loading and unloading operations. This will be more important on the battlefield side of operations. AGVs and AS/RS systems are available today, and smarter versions integrated with planning algorithms should appear in the marketplace for 21st century operations in military and industrial environments.[21]

Finding "Lost" supplies: Getting the correct product to the field location that needs it can also be a problem. A "smart card" for tracking of supplies could be attached to the supplies for location purposes. The card would record what is inside the container it is attached to, and send a signal out periodically to aid the troops in finding the supplies that have been delivered for them. The concept here is not beyond technical capabilities, but the communication method selected for this card's signal will need the same sorts of security/stealth that is envisioned for other distributed force communication capabilities (e.g., soldier 911).[11]

All these human-assisted platforms result in faster deployment of troops and their supplies, plus reduction of personnel and time through improved efficiency of logistical operations.

Field Maintenance and Repair Aids

Definition

Quicker deployment of troops and their equipment and having smaller units in the field can also be aided by making quicker and easier equipment repairs or maintenance in the field. The technologies described here are similar to world-model building and simulation being done today for robotic environments.

Current State of Technology

Repairs and maintenance in the field today in general requires people, tools, and paper copies of manuals. Conversion to electronic manuals is beginning, and may be implemented in some cases; like your local mechanic's shop, computerized diagnostic equipment is likely in use today. However, specialized training is necessary for these advanced diagnostic systems, and spare parts are whatever you choose to take to the field, or are only as close as the next transport to the field.

Emerging Capabilities

Smart, Hands-free Manuals: Electronic manuals may begin to enter the field in the next few years to replace paper manuals.[10,22] For later versions, we envision integration of smart agents, hypertext and searching aids, and/or heads-up displays to make diagnosis of repairs, and finding the right repair or maintenance instructions easier and quicker. Video clips or animated CAD models of parts would also show assembly or disassembly sequences to the repair person. Voice-activated search could also be included.

X-ray vision repair diagnosis: An “x-ray vision” heads-up display shows a 3D CAD image of an assembly (e.g., an airplane fuselage) in the viewer. For aid in diagnosing a problem beneath the surface (e.g., wiring or hydraulic lines, a pump), the CAD model also shows the repair technician what parts should lie behind the surface s/he is looking at.[20,22] Full 3D assembly models may not typically be created today. However, the effort to do so should drop significantly well within the time frame being studied here, so it is reasonable to expect that such models will be available for integration into such a system. Calibration of the position of the viewer/display to the assembly is an extension of the types of world-model to actual equipment calibration being done today in R&D for unstructured robotic and simulation environments.

In the next steps of repair diagnosis, the technician moves a sensor, which we called the "super stud finder”, over the surface of the assembly. Another view would be overlaid on the screen showing parts actually detected. This concept is similar to through-the-wall surveillance, which is an R&D topic today.[11]

Part “Replicator” in the field: Another field repair and maintenance aid is a part "replicator" with a field manufacturing cell. Metal deposition technology in the lab, and entering industry today, should become available for many applications in military environments; research is being done today for creating parts on submarines out at sea.[22-24] Such equipment with metal powder would be used in the field as a “replicator” to create single spare parts, or the many parts for an assembly, for repairs of equipment in the field. A Field Manufacturing Cell (FMC) could also be used to rapidly assemble the replicated piece parts. The FMC, consisting of robotic manufacturing cells with automated programming features, would be capable of rapidly assembling the replicated piece parts.[25-26] Flexible manufacturing cells like this are entering industry today, but smart part assembly algorithms are still in R&D. One could picture these FMC systems in the back of a typical large military transport truck; auto-alignment characteristics will need to be integrated into these systems to initialize them after moving from one site to another, with its jostling of the equipment which will no doubt occur after the vibration or bumpiness in the road. This auto alignment type of feature is in the lab today, but could be ruggedized for the field environment. (See Figure 8).

Impact

These repair/maintenance aids are expected to make field repair operations easier, quicker and more able to adjust to various mission environments. They can be used to support more distributed small unit operations with fewer people.

Extremely Rapid Mission Design and Deployment Environments

Definition

This section discusses systems, which can be composed of numerous subsystems (e.g., tanks, ships, and planes are subsets of the entire battlefield deployment) and which are capable of programming themselves to perform the specific tasks required for the military operations.

Current State of Technology

Software languages and architectures enabling rapid and reliable reprogramming of systems are now available. Object oriented languages, such as C++, coupled with communications tools, such as CORBA, have enabled the design of systems which have modifiable components. Languages such as Java are further extending this capability by enabling independent sections of code to be easily transmitted and executed via networks.[27]

Emerging Capabilities

Never Far from Home: Networking, especially wireless, technologies are rapidly evolving which will enable platforms to be "electronically" linked anywhere at any time. Reliability, security and data integrity are all technology challenges which are being addressed. With the emergence of these new types of networks, this will enable new capabilities, as is described in the following section, in battlefield and peacekeeping deployment operations.[28]

Impact

Physician -- Heal Yourself: Each given mission has specific attributes which need to be entered into weapons systems. Two examples of this are the geometry of the target (e.g., what does the enemy tank look like) and the geography of the region. Using wireless networks, future weapons systems will automatically know they need this information, locate and download this information from databases, and then use this data to program execution plans (e.g., flight paths or image recognition algorithms). The same is true for other platforms such as a mobile vehicle, an airborne surveillance system, or a deployed sensor package. This will reduce the time required for deploying systems and improve the ability to respond to changing military situations.

Mission Impossible?: Using this approach, entire missions can be rapidly planned, simulated, and modified as situations dictate. High level tasks (e.g., "destroy bunker") are distributed to lower levels of systems until ultimately each task for each system is defined, automatically programmed, coordinated, monitored, and modified. The key is that the platforms, such as the missiles or the aircraft, program themselves so they can immediately respond to changing scenarios.

Advanced Training and Simulation

Definition

As the number of troops decreases, and the technology content of deployed systems increases, there will be an increased need to train personnel on the maintenance and operation of these numerous systems. These training systems must be flexible to handle multiple systems and scenarios, must be cost effective to produce and operate, and most important must be accurate. Training and simulation environments are needed which have multiple inputs, multiple players in dispersed locations, rapid reconfigurability, inherent accuracy, cover <u>complete</u> systems, and have interchangeable real and virtual components.

Current State of Technology

The capabilities of simulation and training environments have advanced tremendously over the past few years. The amount of activity occurring in this area is much larger than can be covered in this paper (see reference 29 for more information). Some key aspects are that the performance of computing platforms has rapidly increased while the costs have decreased. This has enabled higher fidelity models to be generated and, when coupled with the emerging networking technologies, has enabled multiple participants to share in the training and simulation environments. In practicality, today's technology still forces assumptions and simplifications to be made in the training and simulation environments (e.g., homogeneous properties, predefined coefficients of restitution and friction...).

Emerging Capabilities

<u>Is it Real, or is it a Simulation?:</u> Simulation environments are moving beyond "animations" of what a system or mission scenario will look like, to become the actual system itself. This somewhat surprising statement is reflected in many of today's remote systems. What the operator sees is simply the interfaces, not the physical platform. By replacing the physical device with an unseen model of the device, the operator can still drive the system. The technology that is enabling this capability is increased processor speeds which will in the next decade enable real-time analysis of physics such as flexures of parts, flowing of liquids, or the movement of dirt. This "fractal" approach to simulations will enable the high accuracy of complete systems from a micro to a macro scale.[15]

Impact

<u>Where's the Reins?:</u> Highly accurate real-time modeling of systems will enable new capabilities not only in the training of operators but in the design of the platforms themselves. Just as the automobile of the 1920's caused the steering wheel to replace the reins as the input device to steer a carriage, new interfaces will be created to replace those which we are currently using. Heads-up displays are an example of a technology which has already been implemented. What will the future cockpit look like when, if the previously discussed remote capabilities are implemented, that cockpit is not part of the plane but rather a room connected to the aircraft via a satellite system? The partial answer is that the training and simulation environment becomes the actual interface environment for the physical platform. The issue of "is the simulation environment accurate" disappears because it is the actual system the operators will be using during operations.

<u>The 100% Solution:</u> Design of systems using today's virtual platforms always involves compromise. Assumptions are made such as coefficients of restitution, friction properties, and homogenous materials. In the future, increased processing capabilities will enable modeling at the atomic level to be meshed with the macro scale to derive highly accurate, and complete (e.g., sensors, power supplies and gear train friction will all be included) solutions to be derived.

Conclusions

The applications of robotics and related technologies in 21st century military operations are broad. Intelligent mobile vehicles of many sizes will supplement manpower, and micro-robots will enable mission surveillance and reconnaissance not previously possible. Other technologies incorporating telerobotic environments, rapidly reprogrammable platforms, and intelligent planning assistants will provide more flexible and faster operations for small unit troops. Advanced simulations, training aids, and maintenance and repair aids will also further optimize the use of the personnel in the smaller, rapidly deployable units envisioned in the 21st century battlefield. All of the technologies presented in this paper will work together, not simply cooperating, but synergizing their individual capabilities to produce new overall capabilities in the operation of future military missions. Enabling technologies are within reach now. With an appropriate amount of additional investment in these areas, the capabilities described here will be in use in the field in the second decade of the 21st century.

Figure 1: Deployment of Miniature Intelligent Mobile Vehicles

Miniature intelligent mobile vehicles will be used to perform surveillance, intelligence gathering, and targeting missions. These roles will be performed in both urban and field environments. In this particular scenario the mobile devices are being deployed at the front-lines. As they gets closer to their target the larger transport devices will deploy smaller devices which will work together to complete the mission and transmit the information back to the deployment location.

Figure 2: Miniature Intelligent Mobile Vehicles in Urban Operations

In an urban environment, visual stealth can become an important element. Here the transport device is disguised as a brick. These devices, in varying disguises, can be dispersed throughout the urban setting and then deploy their smaller devices to perform mission specific tasks, such as determining who is in a building or generating a facility's layout, when commanded by a remote link.

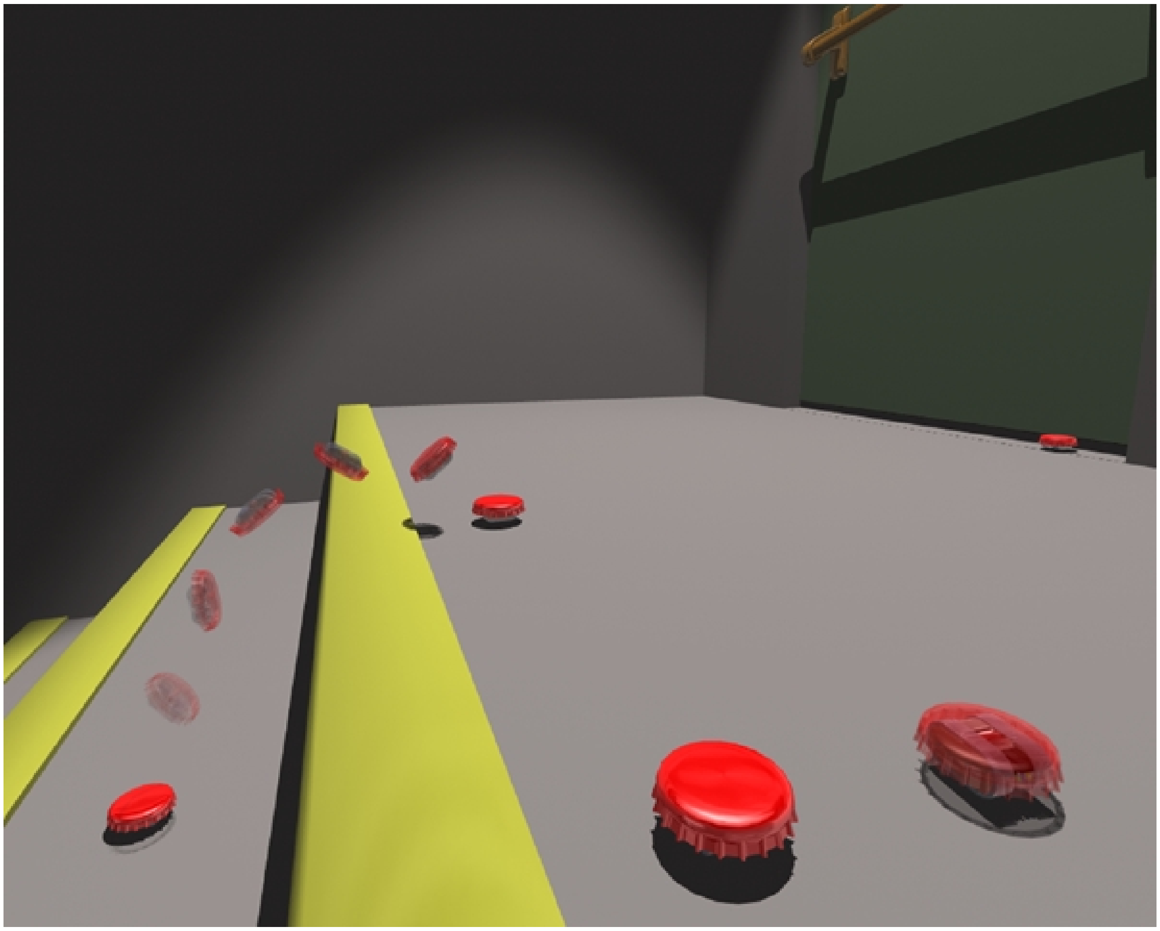

Figure 3: Surveillance, Intelligence Gathering and Targeting in Urban Environments.

Entering a building will at times be required in order to successfully complete missions. In this scenario devices disguised as bottlecaps have been deployed by a transport device (such as in Figures 1 and 2) and are capable of jumping up stairs and sliding under doors as they disperse throughout the building to perform their designated tasks.

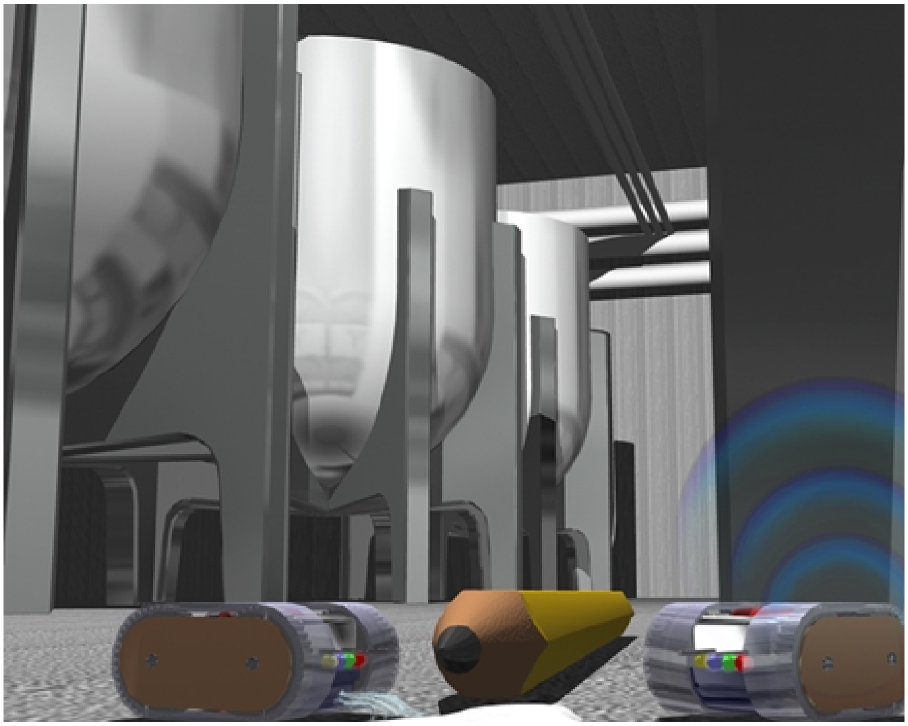

Figure 4: ID Facility Purpose and Layout

Miniature intelligent mobile vehicles will be used to determine a facility's activities, provide weapon guidance, and a post-attack assessment. Another element depicted in this viewgraph is that the mobile vehicles will have different capabilities and work together in achieving the given mission. In this particular case, the one vehicle is equipped with sensors to detect the facility's activities while the other is equipped with long-range communications capabilities to relay this information back to the operators.

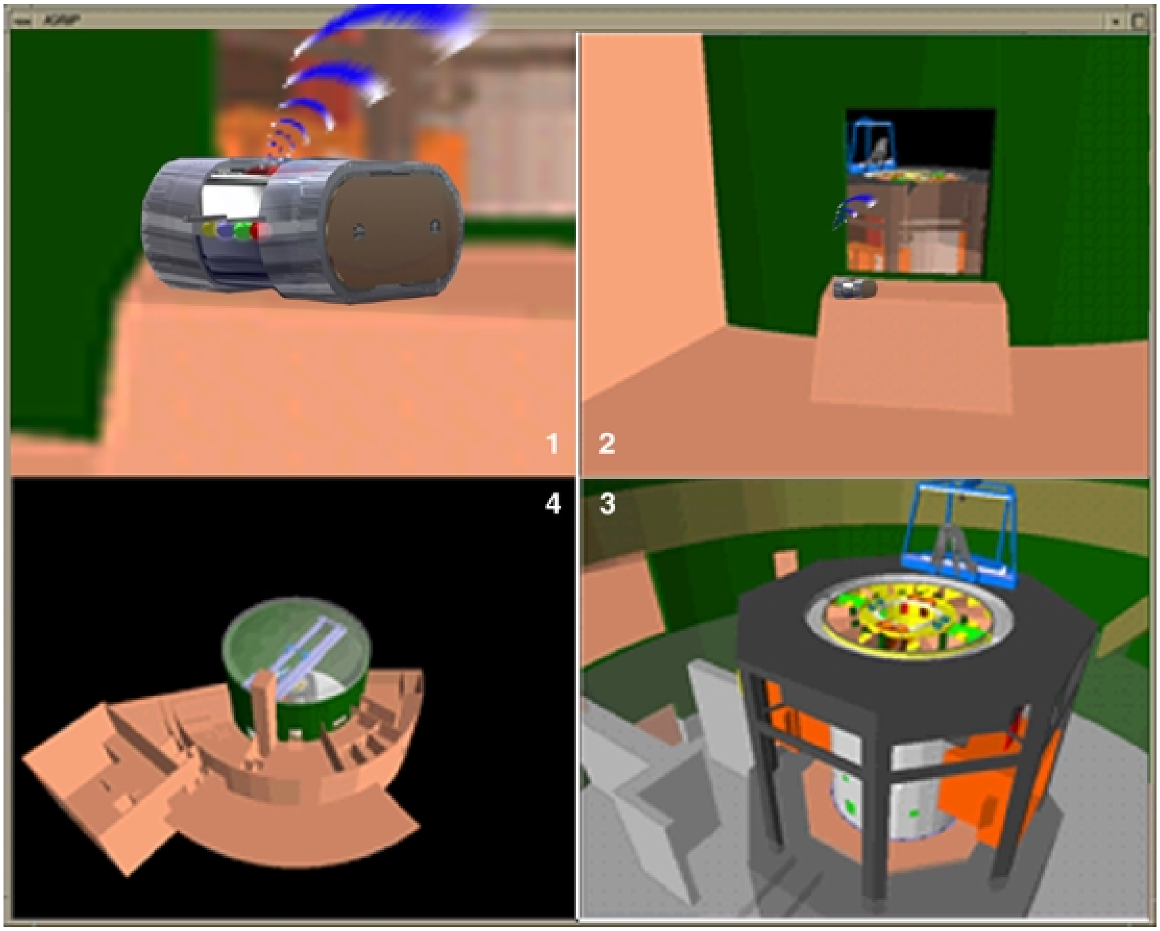

Figure 5: Facility Mapping

The ability to covertly identify the purpose of a facility (e.g., a bunker) and generate a map of its layout will alter both peacekeeping and battlefield operations. This viewgraph depicts a small vehicle entering such a facility, generating a geometric map, and identifying a particular piece of equipment -- in this case detecting the radiation being emitted by the reactor's core.

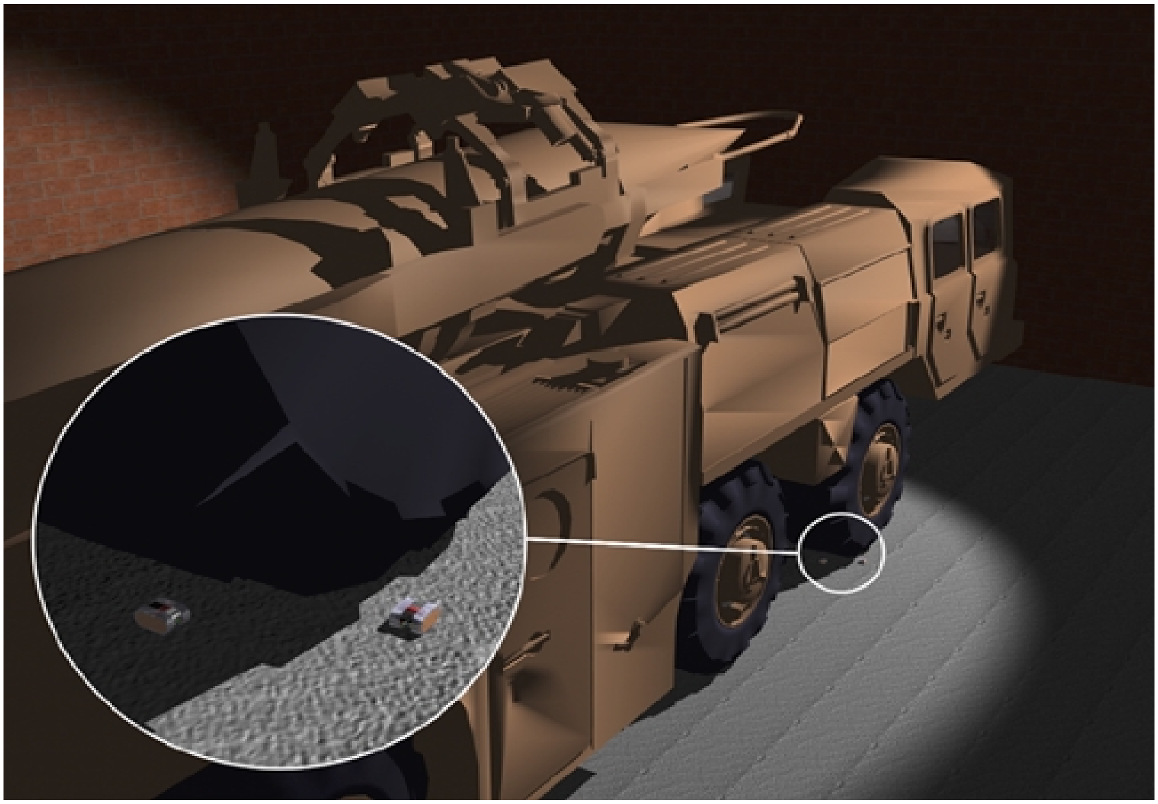

Figure 6: Vehicle ID and Tracking

Tracking the location of vehicles will also provide information on the location of facilities such as missile bunkers or artillery placements. In this scenario we know the enemy is launching missiles from a general area (say 40 square kilometers), but after launch the platform is returned to the bunker before we can act. We could populate this area with devices which would attach to the launcher and provide a tracking capability from which we could determine the location and neutralize the bunker.

Figure 7: Swing Free Cranes in a shipyard

Swing free cranes have been implemented for port-side operations today. Extensions of this technology for swing-free unloading from ships in rough seas is being investigated.

Figure 8: Field Manufacturing Cell in a truck

A system like the Agile Manufacturing Prototype System pictured here, both in a laboratory environment and in a military transport vehicle, could be sent to the field with metal deposition equipment for spare parts "replication" and assembly.

References

[1] "Automation and Robotics Overview", Larry Shipers, Manufacturing Systems Department, Intelligent Systems and Robotics Center, Sandia National Laboratories, Albuquerque, NM.

[2] Y. Matsumoto, M. Inaba, and H. Inoue, "Visual Navigation using View-Sequenced Route Representation," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation,* Minneapolis, MN, April 1996, pp. 83-88.

[3] Dr. Fuchs, Daimler Benz AG - FIM/IA, "Minnesota/Roadstar I: Computer Vision Based Autopilot for an Autonomous Truck," August 1992.

[4] Information on Dante can be obtained from the internet at http://maas.arc.nasa.gov/Dante/

[5] M. Raibert, "Legged Robots That Balance," *MIT Press*, Cambridge, Massachusetts, 1986.

[6] H. Ishihara and T. Fukada, "Micro Autonomous Robotic System," Nagoya University, *Proceedings of the 1995 SPIE Microrobotics and Michromechanical Systems Conference,* Philadelphia, PA, Oct. 25, 1995, pp.32-37.

[7] W. Zesch, R. Buchi, A. Codourey, R. Siegwart, "Inertial Drives for Micro- and Nanorobots: Two Novel Mechanisms," Swiss Federal Institute of Technology, *Proceedings of the 1995 SPIE Microrobotics and Michromechanical Systems Conference,* Philadelphia, PA, Oct. 25, 1995, pp. 80-88.

[8] LIGA = LIthography Galvonoforming Abforming, where Lithography is X-Ray (or deep) lithography, Galvonoforming is electroplate in German, and Abforming is injection molding in German. More information available from John Feddema, Sandia. National Laboratories.

[9] L. M. Desjarlais, "Learning Classifier Systems and Genetic Programming: A Study of Two Methods for Learning Control System Behavior," A Dissertation Proposal to the Dept. of Computer Science, Univ. of New Mexico, April 26, 1995.

[10] Demand for portable Tactical Information Assistants projected in the hundreds of thousands across the military versus non-portable systems, Army Infantry projected at ~150,000 alone; DARPA Electronics Technology Office, tactical information assistant presentation, http://molothrus.sysplan.com/eto/tia/Presentation/TIAManage/slide3.html Other slides in this presentation address maintenance aids.

[11] DARPA, Tactical Technology Office, Overview, Defense Science Board, Dr. David Whelan, 3/19/96.(IUGS, dispersed small unit operations, “Soldier 911” concept, through-the-wall surveillance).

[12] Similar to Loiter Weapons from “Thoughts on Technology Based Concepts” George Heilmeier, Bellcore.

[13] D. S. Horschel, C. Q. Little, and P. T. Boissiere, “Advanced Operator Interfaces for a Remote Mobile Manipulation Robot,” *SAE International Conference on Environmental Systems*, San Diego, CA, July 10-13, 1995.

[14] R. J. Anderson and K. W. Lilly, “A Modular Approach to Multi-Robot Control,” *IEEE Conference on Decision & Control*, New Orleans, LA, December 1995.

[15] M. J. McDonald and R. D. Palmquist, “Graphical Programming: On-Line Robot Simulation for Telerobotic Control,” *International Robots and Vision Automation Show*, Detroit, MI, April 1993.

[16] D. J. Cannon, “Virtual Tools with Attributes for Robotic based Intermediate Manufacturing Processes,” *Proceedings of the 1996 IEEE International Conference on Robotics and Automation*, Minneapolis, MN, April 1996, pp. 1845-1850.

[17] Bird, J. D. III, “A Methodology for the Evaluation of Alternative Amphibious Material Handling Systems,” PhD Dissertation, University of Virginia, August 31, 1979, pp. 67-70.

[18] J. T. Feddema, B. J. Petterson, and R. D. Robinett, “Swing-Free Operator Crane Control with Input Filtering and Feedback,” Patent application: SD-5567.

[19] G. G. Parker, R. D. Robinett, B. J. Driessen, and C. R. Dohrmann, "Operator In-the-Loop Control of Rotary Cranes", SPIE 1996 Symposium on Smart Structures and Materials, Industrial and Commercial Applications of Smart Structures Technologies, February 1996.

[20] The concept of a “Logistics Anchor Desk”, expected in approximately 2001 to provide “expert ‘virtual staff’ assistance to theater and deployed joint task force logistics staffs.” Logistics for the Warrior program, Planning and C3 division of the Information Systems Office (ISO), DARPA; DARPA/ISO is at http://yorktown.dc.isx.com/iso/; Planning and C3 division of DARPA/ISO is at http://yorktown.dc.isx.com/iso/planning/index.html. Also may be related to work being done in the DARPA/DLA Initiative on Logistics Research and Development program which can be found at the above Planning and C3 address.

[21] Materials Handling Research Center sponsored by NSF at Georgia Tech, p80, “Modern Materials Handling” Vol 51, No. 5, Mid-April 1996.

[22] VuMan, MARSS (Maintenance and Repair Soldier System by McDonnell Douglas), DARPA/ Electronic Technologies Office, Smart Modules Program presentation http://eto.sysplan.com/ETO/TIA/Presentation/SmartMod/ Presentation/slide1.html

[23] Sandia National Laboratories, Department 1831, Laser Engineered Net Shape System, Mike Cieslak, Albuquerque, NM.

[24] F. G. Arcella, E. J. Whitney, and D. Krantz, "Laser Forming Near Shapes in Titanium," *ICALEO 1995 International Congress on Applications of Lasers and Electro-Optics, Laser Materials Processing,* San Diego, CA, November 13, 1995.

[25] P. Garcia et. al., Agile Manufacturing Prototyping System, *5th Agility Forum*, Boston, MA, April 1996.

[26] R. E. Jones and R. H. Wilson, "A Survey of Constraints in Automated Assembly Planning," *Proceedings of the 1996 IEEE International Conference on Robotics and Automation,* Minneapolis, MN, April 1996, pp. 1525-1532.

[27] Information can be obtained about the Java programming language at http://www.yahoo.com/Business_and_Economy/Companies/Computers/Software/Programming_Tools/Languages/Java/

[28] Information on wireless communication capabilities can be found in abundance at http://www.yahoo.com/Business_and_Economy/Companies/Computers/Networking/Wireless/

[29] DARPA, Information systems Office (ISO), Simulation Division, is involved in a Synthetic Theater of War, (STOW 97 ACTD) Advanced Concept Technology Demonstration. The STOW system is scheduled to currently be completing Conceptual Design Review. The STOW 97 ACTD demonstration is scheduled in March 1998. See more info at http://yorktown.dc.isx.com/ iso/simulate/index.html under Advanced Distributed Simulation, Real-time Information Transfer and Networking, Synthetic Environments, Synthetic Forces, and STOW Systems.

[30] list of videos which may be of interest as background for this paper:

- Sandia Military Robotics Technology, 4/20/93, rg 1A15
- Interwoven Virtual and Physical Reality, 4/23/93, D. Cannon, Penn State University
- Sandia Intelligent Systems and Robotics Overview, 5/95, JL
- Sancho -- Virtual Collaborative Environment, 3/21/96, DS
- Swing-Free Transport, Operator-in-the-loop with Variable Rope Length, 9/94, JF
- Swing-Free Control -- MSPA Container Crane, 11/94, JF

Distribution:

Jill Fahrenholtz
1014 Iron Horse Road
Rolla, MO 65401

Robert Palmquist
ViA Inc.
11 Bridge Square
Northfield, MN 55057

5	MS1004	ISRC Library, 15221
1	MS9201	R. M. Wheeler, Jr., 8112
1	MS9018	Central Technical Files, 8940-2
2	MS0899	Technical Library, 4916
2	MS0619	Review & Approval Desk, 12690 for DOE/OSTI